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TRENDS IN HIGH-SPEED ATMOSPHERIC FLIGHT

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Summary

Some of the current problems and future trends for three types of flight within the Earth's atmosphere are considered. The three areas examined are atmosphere entry at very high speeds, atmosphere exit of launch vehicles, and sustained cruise within the atmosphere.

The high-speed entry problems described are those encountered by vehicles returning to Earth after a manned mission to Mars. Such vehicles will experience atmosphere entry speeds up to 50,000 and perhaps as high as 70,000 feet per second. For these vehicles to execute a successful entry, accurate guidance at Earth approach must be provided and very precise control during the flight within the atmosphere will be a necessity. At the high entry speeds radiative heating is greater than convective and thus it tends to exert a dominant influence on entry-vehicle configuration. The study and development of relatively slender vehicles is indicated in order to minimize the large radiative heating loads and associated heat-shield weights.

Manned interplanetary missions in the future may also involve a need for very large launch vehicles. These large vehicles will have aerodynamic problems which differ somewhat from current problems. For example, drag losses decrease with increasing size and large vehicles may thus be of lower fineness ratio than present-day vehicles. With lower fineness ratio some of the difficult current problems produced by ground-wind loads and by buffet of hammerhead payload mountings will be avoided.

In the case of high-speed cruise within the Earth's atmosphere, the use of hydrogen-fueled, air-breathing engines may permit attractive payload capabilities for long-range high-speed transports. For such vehicles aerodynamic problems arise because of the numerous constraints placed upon their flight paths as well as from the large volumes required for the hydrogen fuel. From payload considerations alone, attractive cruise speeds for such vehicles currently appear to be about twice that of the conventionally fueled supersonic transports now being intensively studied.

Atmosphere Entry

With the Mercury project now complete, and with the Gemini and Apollo programs well along the route of hardware development, current studies of atmosphere entry are directed toward other problems. Interest is being shown in several areas including maneuvering entry (particularly from satellite orbit), entry at hyperbolic speeds (i.e., Earth entry speeds greater than 36,000 ft/sec), and entry into the atmospheres of other planets. For maneuvering entry, the mechanics of the problem have been well known for some time[1-3] and current interest is largely centered on the study of maneuverable entry configurations, particularly lifting bodies. A summary of past work with lifting bodies has been prepared by Becker[4]; other papers on this subject are also available.[5,6] One of the most interesting developments of the past year was the piloted flight of a lifting body.[7] These flights were made at the NASA Flight Research Center with the M-2 configuration built as a lightweight glider that could be towed to altitude by a C-47. A photograph of the glider in flight is shown in Fig. 1. The pilot in the picture is Milton O. Thompson of FRC who made the first flights. He and other pilots have made repeated successful landings with the glider. The program is now being expanded and future flights will be made with heavier and faster vehicles and with other configurations as well.

Entry into the atmosphere of planets other than Earth is also an active subject at the present time. Much of this work has been concentrated on the problems associated with Mars. Some of the major problems for entry into the martian atmosphere are discussed by Seiff[8,9] and, for this reason, attention in the present paper will be confined to the problems associated with entering the Earth's atmosphere after a round trip to Mars.

Many of the major aspects of a manned interplanetary mission to Mars have been examined in a series of studies.[10-16] Opportunities to send men to Mars occur about once every 26 months; this interval is associated with the period between oppositions of Mars and Earth. However, there is considerable variation in the distance between Earth and Mars from one opposition to the next, and associated with this variation is a relatively large variation in the Earth entry speed. This variation is indicated in Fig. 2 where Earth entry speeds associated with some of the more attractive round trips to Mars are shown for opportunities between 1971 and 1999. The entry speed varies from about 47,000 to about 68,000 feet per second with a cyclic period of about 15 years. It is possible, however, to reduce the higher speeds and to eliminate much of the variation from year to year if appropriate use is made of a close fly-by of Venus. As the sketch in Fig. 2 indicates, the gravitational field of Venus can be used to deflect the interplanetary return trajectory in a manner to reduce the angle between the trajectories of the vehicle and of the vehicle and of Earth. This technique has been explored by Sohn[14] in a contracted study for the NASA Ames Research Center. The reductions in Earth entry speeds it permits are indicated by the shaded sections in Fig. 2. In general, this use of Venus results in entry speeds below 50,000 feet per second in all cases studied to date. Since many facets of the use of Venus fly-bys remain to be explored, it is concluded from these results that Earth entry speeds up to 50,000 and perhaps as high as 70,000 feet per second will be associated with a manned trip to Mars.

Entry at these speeds presents some major problems; for example, entry corridors are considerably more narrow than at the entry speed of Apollo. This reduction in corridor depth is evident in Fig. 3 where results obtained with the earlier works of Chapman[17] and Wong and Slye[18] are shown. The usual definition is used - that corridor depth is the difference in height of the vacuum perigees of two conic trajectories. If the vehicle approaches above the upper or overshoot trajectory, insufficient air is encountered to achieve capture; if it approaches below the lower or undershoot trajectory, the decelerations experienced by the vehicle exceed a specified value. The corridor depths indicated in Fig. 3 are those for a specified maximum deceleration of 10g and for vehicles with lift-drag ratios of 0, 1/2, and 1. If 10 miles represent a reasonable minimum depth to accommodate guidance inaccuracies and uncertainties in the atmosphere, ballistic vehicles (L/D = 0) cannot be used for entry speeds above about 35,000 feet per second. Vehicles with lift-drag ratios of 1/2 (such as Apollo) can be used up to about 65,000 feet per second. At higher speeds, however, vehicles with lift-drag ratios up to 1 would be required.

Entering within the allowable corridor is not the only problem. Once within the corridor it is necessary to avoid maneuvers which could produce excessive accelerations or which could eject the vehicle from the atmosphere. One possible type of problem is illustrated in Fig. 4. For this example, a vehicle was considered with a lift-drag ratio of 1 entering at 65,000 feet per second near the undershoot trajectory. When an entry vehicle operates near undershoot, it normally enters in an upright attitude and with positive lift. Soon after maximum deceleration, it is rolled over to achieve negative lift. This maneuver prevents the vehicle from skipping out of the atmosphere. For the results shown in Fig. 4, the roll-over was considered to occur instantaneously but its execution was varied from a few seconds ahead of the nominal time to a few seconds after. The results show that if the maneuver were to be executed as little as 5 seconds too soon, the maximum deceleration would be doubled to 20g. If it were 1 second too late, the vehicle would skip out of the atmosphere. While the maneuver considered in Fig. 4 represents a great simplification of the actual way a vehicle might be operated, the results do indicate the sensitivity of maneuvering within the atmosphere at 65,000 feet per second, and they also illustrate the severity of the guidance and control problems associated with interplanetary missions.

It is obvious that aerodynamic heating will be another major problem at these speeds. Radiative heating is of particular concern[19-21] since it increases very rapidly with speed, at least as the 8th power of the velocity. This rapid increase becomes a major factor in the design of heat shields and tends to exert a controlling influence on the selection of entry-vehicle configurations. It is somewhat interesting to note that Allen, who was the first to suggest the use of blunt entry bodies,[22] has shown in a more recent paper[23] that pointed bodies are more attractive at the high entry speeds where radiative heating is so important. Since these basic results are discussed by Seiff,[8] attention here will be restricted to some estimates of heat-shield weight which will provide examples of the significance of radiative heating. These estimates are presented in Fig. 5 where the ratios of heat-shield weight to total weight at entry are shown as a function of entry speed for three shapes.[13,16] First of these shapes is the Apollo configuration which, at its design entry speed of 36,000 feet per second, has the lightest heat shield; however, because of the bluntness of the Apollo shape, radiative heating causes a rapid increase in heat-shield weight making the shape somewhat unattractive at speeds above about 45,000 feet per second. The second shape is the so-called M-1 configuration which is approximately one-half of a blunt 30° half-angle cone. Since this shape is considerably more slender than Apollo and has only a relatively small spherically blunt nose, the radiative heating is considerably less and the heat-shield weight does not increase nearly as rapidly with increasing speed. Even this shape is too blunt, however, and reducing the radius of the blunt nose by a factor of 4 results in a considerable saving in heat-shield weight at the higher speeds. While many approximations were required to obtain these results, they do illustrate the important effect that radiative heating will have on the selection of vehicles for use at the high entry speeds associated with interplanetary missions. Even for the best of the example shapes, however, the heat shields represent approximately 50 percent of the entry-vehicle weight at the higher speeds. These heat shields are very heavy compared to those of current vehicles. In spite of the large shielding weights, the use of atmosphere braking to decelerate a vehicle as it encounters a planet is still very attractive compared to propulsive braking. Just how attractive is illustrated in Fig. 6.

The results presented in Fig. 6 are estimates of the weights that must be placed in Earth orbit in order to accomplish a manned round trip to Mars.[16] The three bars on the left represent these weights when chemical systems are used for major propulsive maneuvers in space; the three on the right represent those when nuclear propulsion is used. In each case, the left of the three bars indicates the weight in Earth orbit associated with using propulsive braking both to decelerate into orbit abouts Mars and to decelerate at Earth return to an entry speed of 36,000 feet per second (i.e., the entry speed of Apollo). The middle bar indicates the weight associated with using propulsive braking only at Mars and only atmosphere braking at Earth return. In this case, of course, the entry speeds are considerably greater than the 36,000 feet per second of Apollo. Using atmosphere braking for this maneuver results in a saving in Earth orbit weight of about 40 percent. When atmosphere braking is also used to establish an orbit about Mars, a further weight saving of 20 to 40 percent is possible, as is shown by the right bar in each case. These comparisons show that the use of atmosphere braking, wherever it is possible, will represent very large savings in the launch vehicle requirements associated with manned interplanetary missions. An indication of these savings is given by the short scale to the left which shows the number of Saturn V launch vehicles required to place a given weight in orbit. Even with atmosphere braking, required weights are the order of a million pounds and for this payload, rendezvous of several Saturn V vehicles would be required. For this reason, it may be desirable to develop a vehicle capable of the required payload in a single launch. Like all launch systems, this vehicle would spend part of its flight within the atmosphere. Accordingly, the next subject will be the atmospheric flight problems of launch vehicles.

Atmosphere Exit

Launch vehicles are subject to several aerodynamic problems during their exit from the atmosphere. Three of these are associated with ground winds, buffet, and drag losses.

In one sense at least, launch vehicles are unique in that they encounter their first aerodynamic problem before they are in flight. This problem results from ground winds which can produce relatively large bending moments in a launch vehicle. Usually, the troublesome moments are those due to gusts and drag forces and those due to lateral oscillatory loads produced by the shedding of vortices from the cylindrical sections of a vehicle.[24] Such oscillatory loads are often encountered by smoke stacks. For some typical launch vehicle arrangements, Fig. 7 presents the magnitudes of bending moments produced by the oscillatory side loads.[25] For reference purposes, the moments due to steady drag loads are shown by the dashed curve. For relatively clean sharp-nosed launch vehicles, the oscillatory side loads are smaller than the drag loads as is indicated by the shaded band. Unfortunately, many launch vehicles have blunt noses, have conduits down their sides, and require umbilical towers. Each of these changes from the clean, sharp-nosed configuration can result in an order of magnitude increase in the oscillatory loads as is shown in Fig. 7. With the increase the resulting oscillatory loads in a gentle 30-mile-per-hour wind can be greater than the steady loads in a 90-mile-per-hour gale. Unfortunately, generally applicable preventive measures do not seem to be available and, for this reason, each launch arrangement must often be studied for its individual problems.

The next aerodynamic problem encountered by a launch vehicle is usually buffet.[26] In most cases, if serious buffet occurs, it is encountered near transonic speeds. Buffet is often experienced by so-called hammerhead launch vehicles. The term hammerhead is generally used to describe shapes where the payload is larger in diameter than the upper sections of the launch vehicle. With such arrangements, buffet can result either from an excessively blunt nose or from separation on the boattailed fairing between payload and launch vehicle. Whether or not a serious buffet problem will be encountered by a particular hammerhead shape is a very subtle question. Just how subtle is illustrated in Fig. 8. At the top of Fig. 8 are sketched three hammerhead shapes which, according to specific transonic wind-tunnel tests, have unacceptable buffet characteristics.[27] At the bottom, three other shapes are shown which have acceptable buffet characteristics. The differences in the two groups are evident only after a very careful examination. These shapes were, of course, selected to demonstrate that buffet problems often cannot be anticipated by a simple and cursory examination of shape. In fact, few general rules seem to exist for the avoidance of buffet and, more often than not, resort must be made to experimental programs to ascertain if a particular design is indeed acceptable.

At this point it should be apparent that the aerodynamic problems produced for launch vehicles by both ground winds and buffet are usually difficult and often impossible to analyze. By contrast, the third problem to be examined here is amenable to a nearly trivial analysis. In particular, it is very easy to show that the integrated velocity loss due to drag suffered by a launch vehicle as it traverses the atmosphere is inversely proportional to W/C_DA, the familiar ballistic parameter.[28] Based on the trajectory calculations for a variety of present-day, liquid-fuel launch vehicles, a reasonable correlation is

$$\Delta V_{drag} \approx (5\times10^6)/(W/C_DA)$$

where ΔV is the drag loss in feet per second; W is the launch weight in pounds; C_D is the subsonic drag coefficient; A is the drag reference area in square feet. The correlation is illustrated in Fig. 9 where both this equation and results of calculations for individual launch vehicles are presented. While the correlation appears reasonable, the important fact is that the drag loss decreases significantly with increasing vehicle size. This trend is easily understood since with other factors equal the ballistic parameter increases as the one-third power of weight. With drag losses decreasing with increasing weight, large launch vehicles need not have low-drag shapes and thus can be of lower fineness ratio. One example which tends to confirm this trend is shown in Fig. 10. The illustrated shape is the Rombus vehicle being studied by industry under the auspices of the NASA Marshall Space Flight Center.[29] It should be recognized, of course, that many other factors influence the launch-vehicle shape, for example, the use of advanced engines such as the segmented plug-nozzle engine on Rombus, Fig. 10. The trend toward lower fineness ratios in large launch vehicles appears, however, to be a valid one. For this reason, some of the problems associated with current launch vehicles may be less severe with future vehicles. Certainly, ground winds should be of less concern, and the need to employ hammerhead shapes will, hopefully, be reduced. Rather, the launch-vehicle aerodynamic problems which may be of most interest in the future are those associated with recoverability. This subject was summarized recently in a series of articles.[29-34]

Atmosphere Cruise

Several problems of atmosphere entry and of atmosphere exit have been treated and it remains now to examine some problems associated with conventional or near-conventional aircraft. The one aircraft which is perhaps most closely related to the space vehicles considered thus far is the X-15. On January 21 of this year, these research airplanes completed their 100th flight. The X-15 program has been summarized in two recent papers, one by Becker[35] and one by Toll and Fischel;[36] thus a further summary will not be attempted here. For much the same reason, work on the supersonic transports will not be reviewed since it is also summarized elsewhere.[37-39] Rather, attention will be confined to aircraft which could follow the X-15 and the supersonic transport and which, in certain respects, are related to both of these. These future vehicles are hypersonic transports.[40] From some viewpoints, at least, this name is not properly descriptive since the results of several papers soon to be published on the subject indicate that the most characteristic feature of these transports is not their speed but rather their fuel, hydrogen. These papers include one by T. J. Gregory, R. H. Petersen, and J. A. Wyss to be given at the AIAA Transport Aircraft Design and Operations Conference, Seattle, Washington, on Aug. 10-12, 1964, and one by R. J. Weber to be given at the 4th International Congress of the International Council of the Aeronautical Sciences, Paris, France, on Aug. 24-28, 1964. The importance of the hydrogen fuel can be illustrated with the aid of the Breguet factor. In Fig. 11, this factor (i.e., the product of airframe lift-drag ratio, engine specific impulse, and velocity) is shown as a function of cruise Mach number for three different types of aircraft. The three aircraft types are subsonic and supersonic turbojet transports operating with JP fuel and a hypersonic transport using turboramjets with hydrogen fuel. It is apparent from these curves that the Breguet factors for hydrogen-fueled transports are significantly greater than those for the other two. It is thus suggested that the hydrogen-fueled aircraft should have substantial range and payload capabilities. The property of hydrogen that results in this capability is, of course, its heat of combustion which, as is shown in Fig. 11, is more than 2-1/2 times that of JP fuels. The major disadvantage of hydrogen, which is also indicated in Fig. 11, is its low density which is less than one-tenth that of JP fuels.

A favorable Breguet factor for cruise does not insure superior transport performance. Results of supersonic transport studies have shown that the climb and acceleration portions of flight can have a greater influence on aircraft characteristics than can the cruise portions. Some considerations which affect the climb and acceleration of turboramjet-powered, hypersonic aircraft are illustrated in Fig. 12 where, among other things, typical cruise altitudes are indicated. From take-off to these cruise conditions an aircraft will follow a profile of altitude and Mach number that is the result of several compromises. Performance considerations dictate low altitudes and high speeds while structural considerations dictate high altitudes and low speeds. In addition to these two considerations there are a number of factors. At low speeds, for example, noise is important. At transonic and low supersonic speeds, sonic-boom overpressures are the dictating factor. At Mach numbers between about 3 and 5, dynamic pressures increase very rapidly and structural limits are encountered. At Mach numbers near 5, internal pressures in the propulsion system increase rapidly, and if heavy ducts and engines are to be avoided, altitude must be increased. Finally, at the higher speeds, aerodynamic heating tends to be the predominant consideration. In order to investigate the several trade-offs indicated, a model is needed to relate performance and weight. The present results are based on the relatively simple configuration sketched in Fig. 12. This configuration has triangular wings and was considered to be powered by turboramjets. A comprehensive trade-off study has been carried out for this arrangement by Gregory, Petersen, and Wyss but only representative results will be considered here. For example, a trade-off is encountered in the selection of a suitable fuselage shape. The low density of the hydrogen fuel results in fuselages of great volume which are a major source of drag. Accordingly, aerodynamic considerations suggest fuselages of high fineness ratio but these shapes are not attractive structurally. When both effects are considered, the desired fineness ratio for the transport is the one which results in maximum payload. Results of the trade-off just discussed are shown in Fig. 13. These results are for a transport which weighs 500,000 pounds at take-off and which cruises at a Mach number of 6 with a range of 5,600 nautical miles. Component weights are given as fractions of gross take-off weight. These results show that with increases in fineness ratio, fuel and propulsion system weights decrease as would be expected for the reduction in drag, but fuselage structural weights increase as would be expected from the increasing length. The fineness ratio giving the largest weight for payload and fuel reserves is about 12 or 13. As the sketches indicate, the resulting fuselage is about twice as long as current subsonic transports. Such large fuselages would result in a number of aerodynamic problems not the least of which are those associated with take-off and landing.

The results of this and several other trade-offs give a first approximation of the performance that could be expected from hydrogen-fueled transports. The effects of Mach number on this performance are shown in Fig. 14 where the fractions of the gross take-off weight required for the airframe, propulsion system, and fuel, and that fraction left for payload and reserves are shown for transports cruising at Mach numbers from 4 to 8. Again, these results are for a range of 5,600 nautical miles. The results indicate that a maximum payload fraction is provided by a vehicle that cruises at a Mach number of 6. At Mach numbers above about 6.5, studies have shown that the engine and engine-inlet cooling requirements exceed the heat capacity of the stoichiometric fuel flow. The additional fuel required for coolant then causes a rapid decrease in payload at the higher Mach numbers. The fraction of the weight available for payload at other ranges is indicated in Fig. 15. These results indicate first that a cruise Mach number of 6 is attractive at most ranges. The results also show again that when extra fuel is required for cooling, the payload capability is significantly reduced. Perhaps the most important result, however, is that hypersonic hydrogen-fueled transports are capable of extremely long ranges and have excellent payload capabilities. In the future, then, many studies in the area of atmospheric flight mechanics may be associated with hypersonic transports.

Concluding Remarks

The foregoing brief review of atmosphere entry, atmosphere exit, and atmosphere cruise has suggested that future vehicles in each of these areas will differ significantly from their current-day counterparts. For example, entry vehicles for use in the interplanetary missions which may follow the lunar mission will enter the Earth's atmosphere at speeds up to twice that of Apollo. At these speeds, radiative heating predominates and dictates the use of more slender configurations than the very blunt Apollo. The interplanetary entry vehicles will also require very precise guidance and control both when approaching the Earth and when flying within the atmosphere.

If launch vehicles larger than Saturn V are developed, they could very well be of lower fineness ratio having relatively shorter lengths and larger diameters. These shapes are permitted partly because of a reduction in drag losses with increasing launch-vehicle weight. Such vehicles certainly should be less subject to ground-wind problems and the larger diameters should eliminate arrangements with hammerhead payloads which may have attendant buffet problems.

For cruise aircraft that follow the supersonic transports, the most characteristic feature will be the probable use of hydrogen fuel. This high-energy fuel provides excellent payload and range capabilities for transports flying up to about twice the speed of the supersonic transport. The low density of the fuel results in aircraft with very large fuselages which may be twice the size of current-day subsonic jet transports.

In all of the areas examined, then, significant changes in future configurations are suggested. Each of these new vehicles may be expected to present a variety of new problems in atmospheric flight mechanics.

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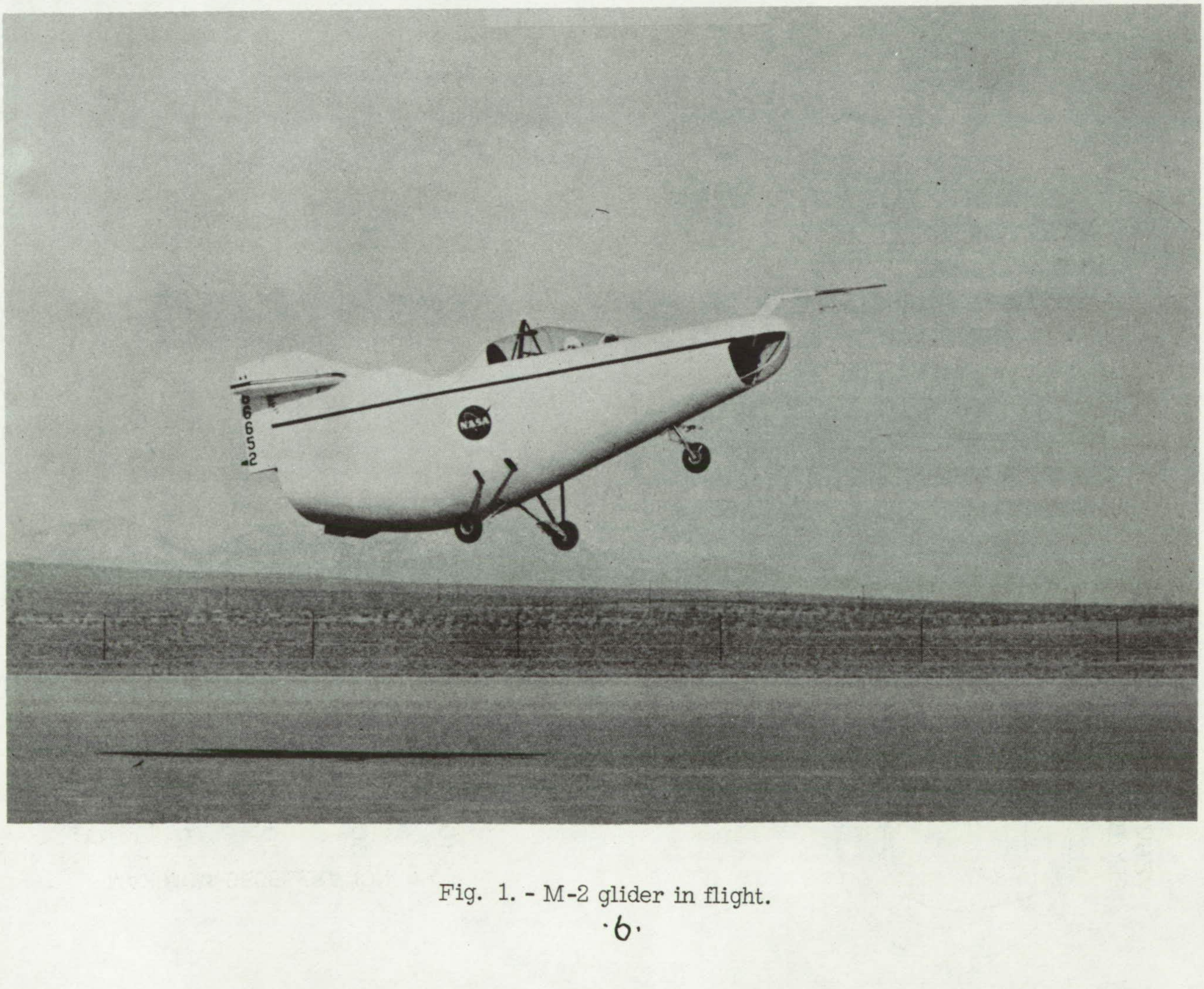

Fig. 1. - M-2 glider in flight.

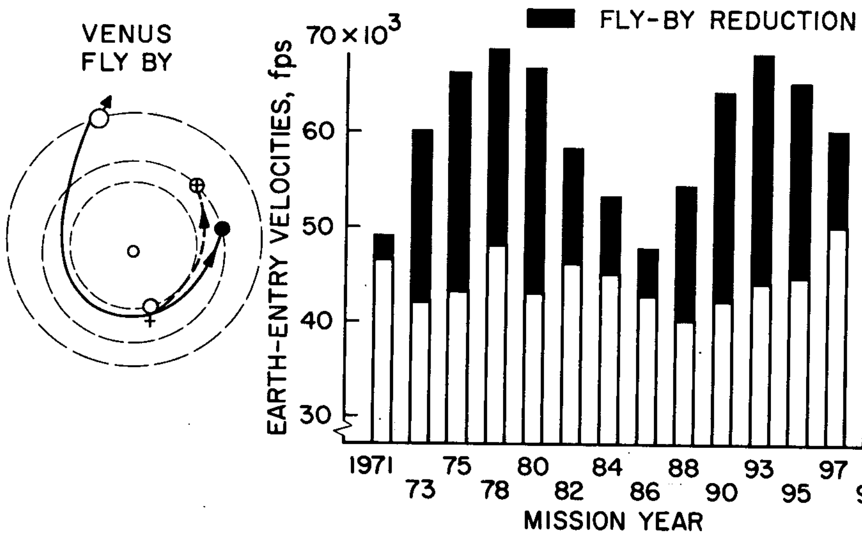

Fig. 2. - Earth entry velocities.

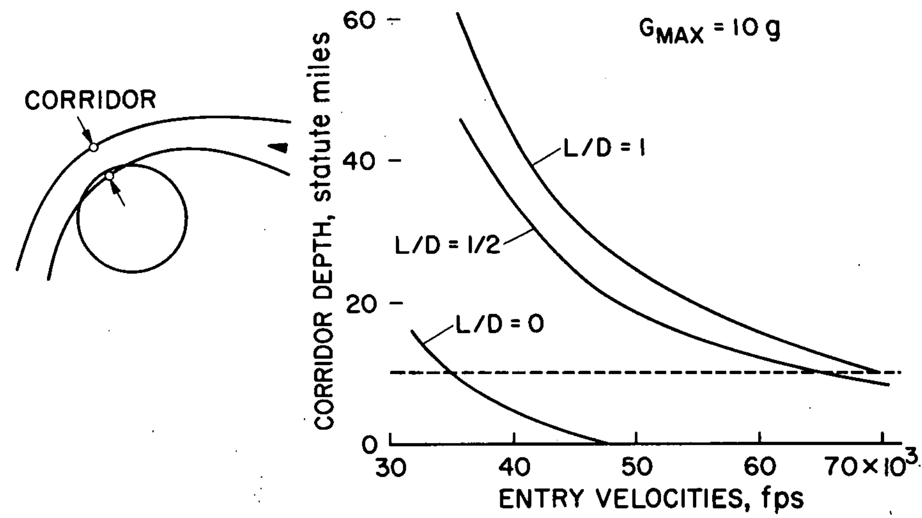

Fig. 3. - Earth entry corridors.

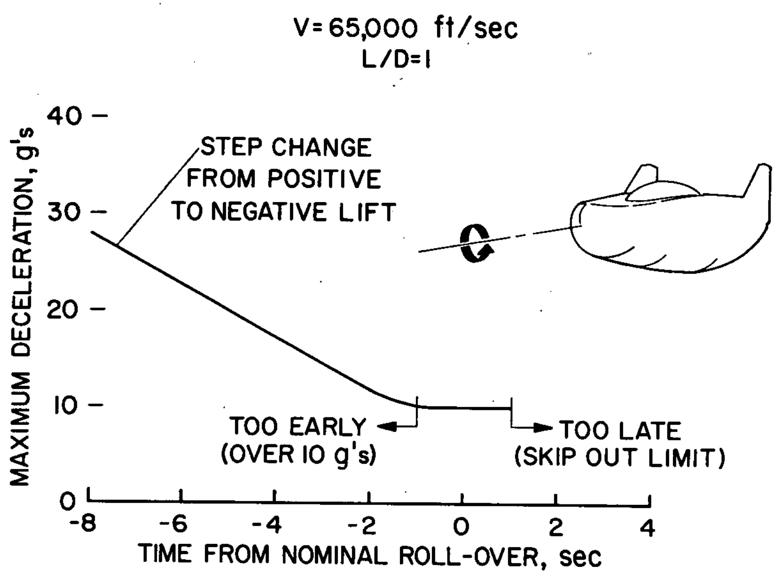

Fig. 4. - Entry at undershoot boundary.

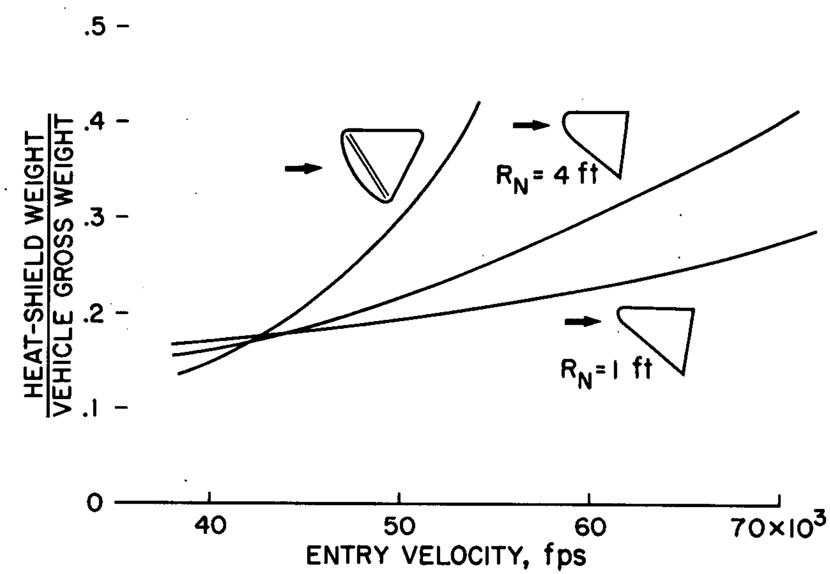

Fig. 5. - Heat shields.

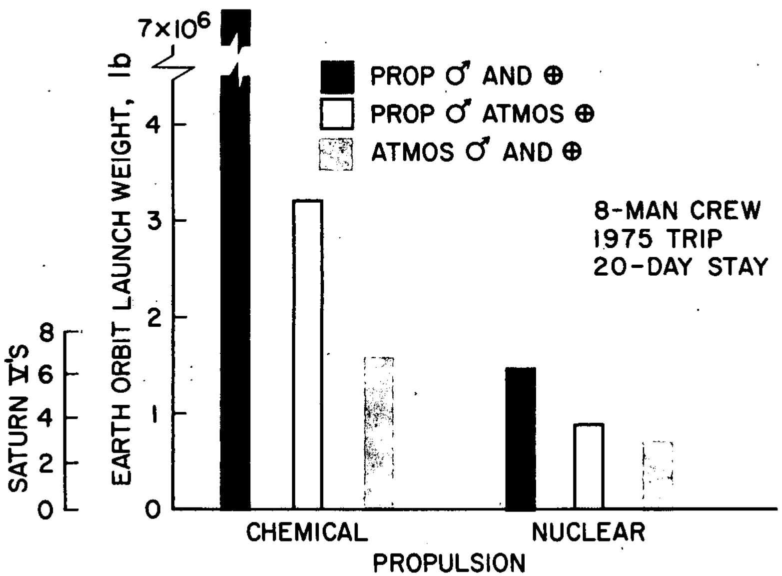

Fig. 6. - Earth orbit launch weights.

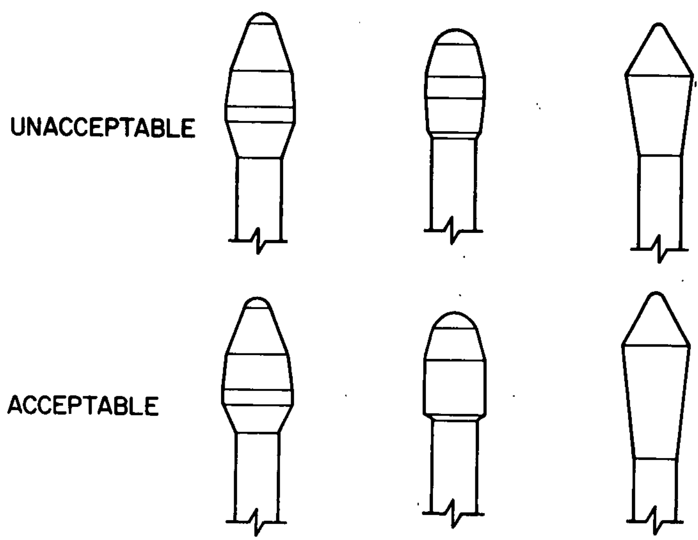

Fig. 8. - Launch-vehicle buffeting.

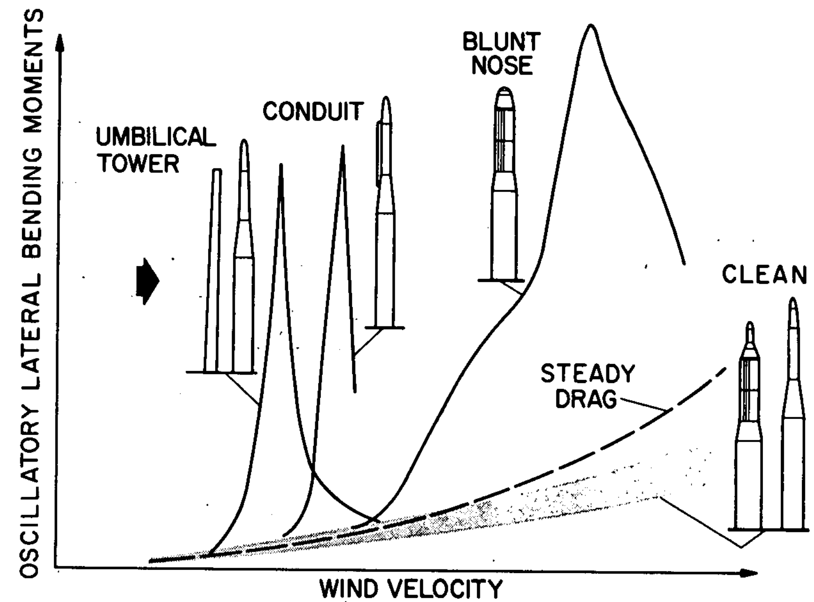

Fig. 7. - Ground-wind loads.

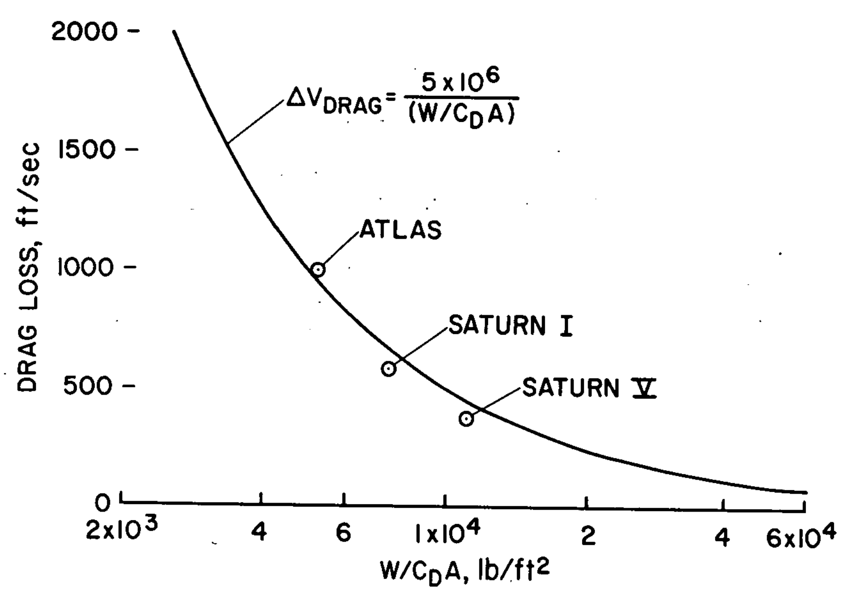

Fig. 9. - Launch-vehicle drag loss.

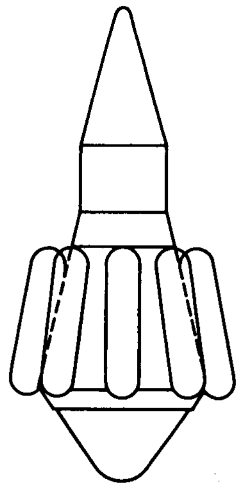

Fig. 10. - Advanced launch-vehicle concept.

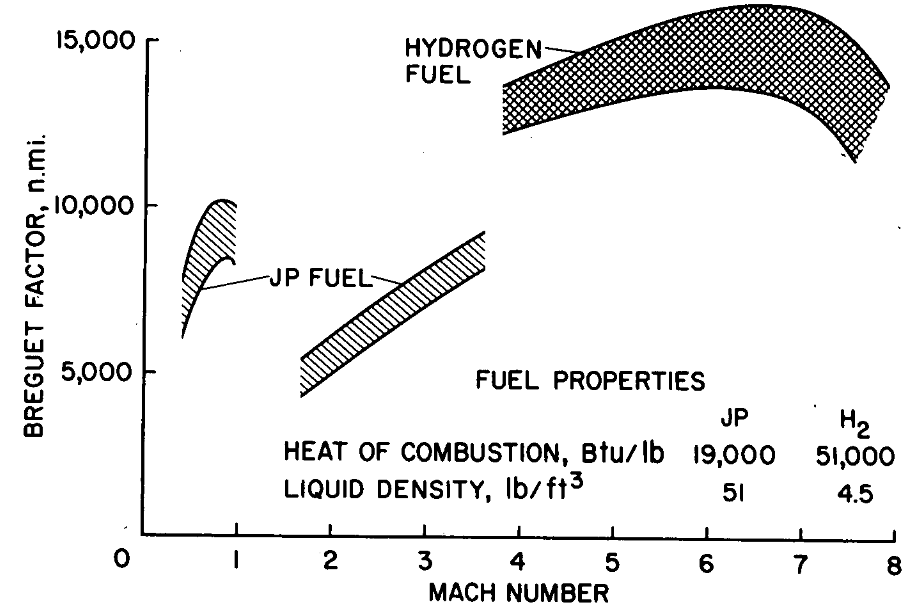

Fig. 11. - Hypersonic transport potential.

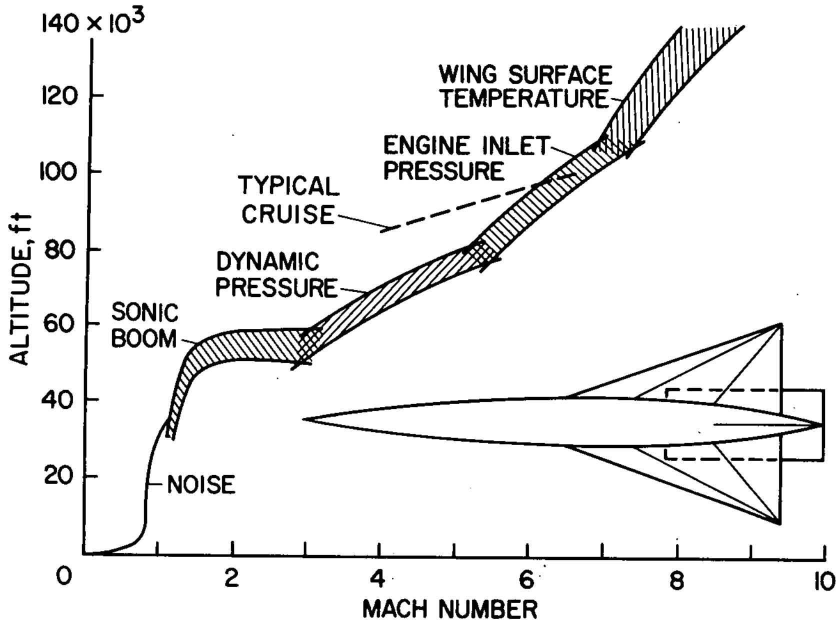

Fig. 12. - Trajectory constraints.

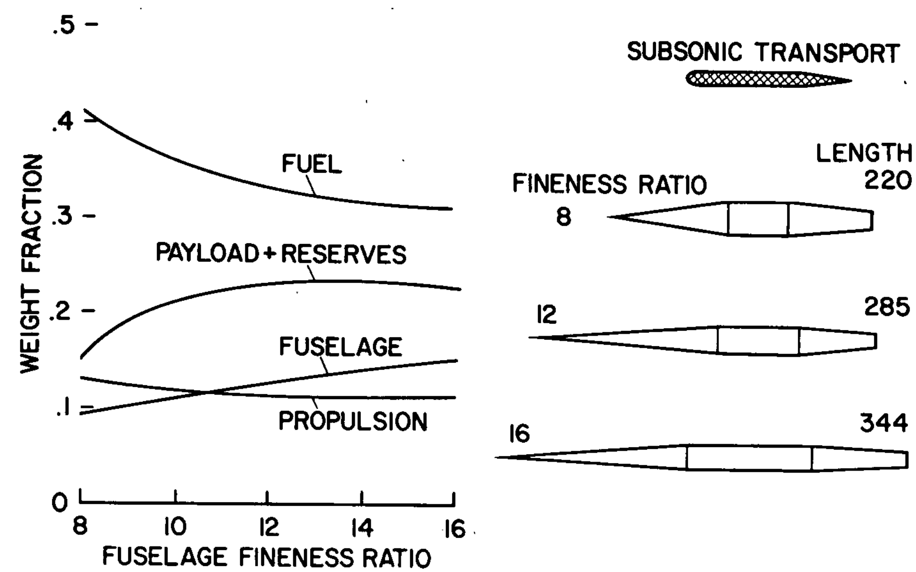

Fig. 13. - Influence of fuselage fineness ratio.

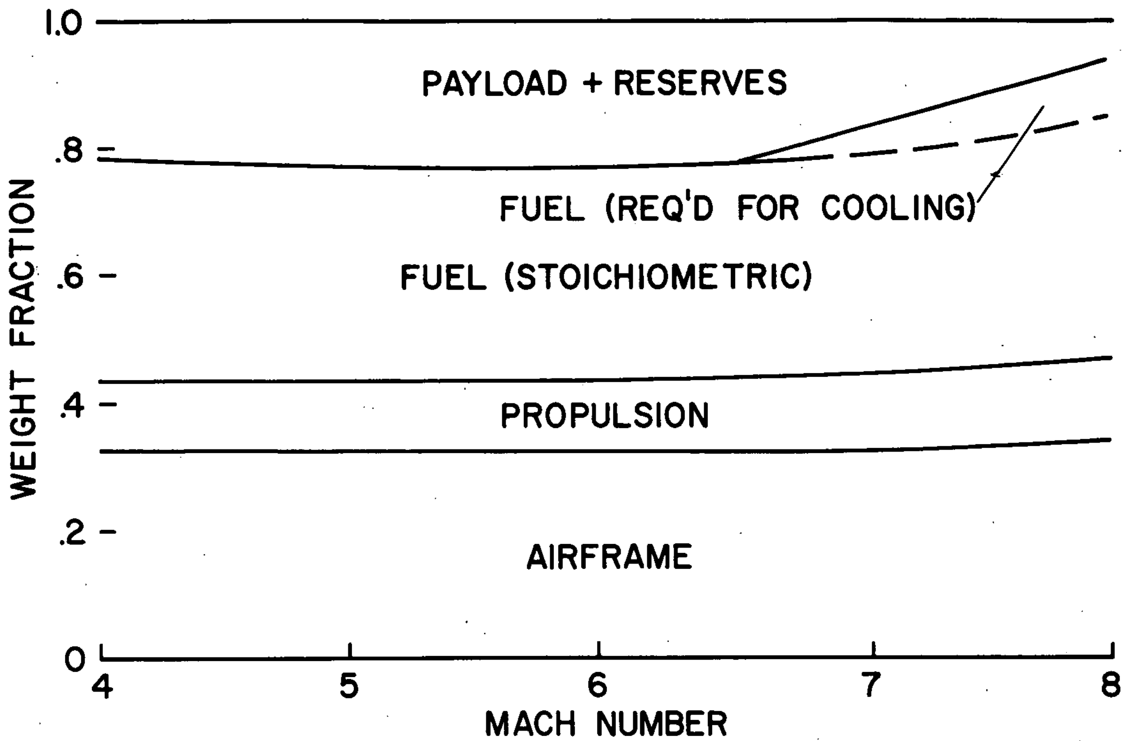

Fig. 14. - Cruise Mach number

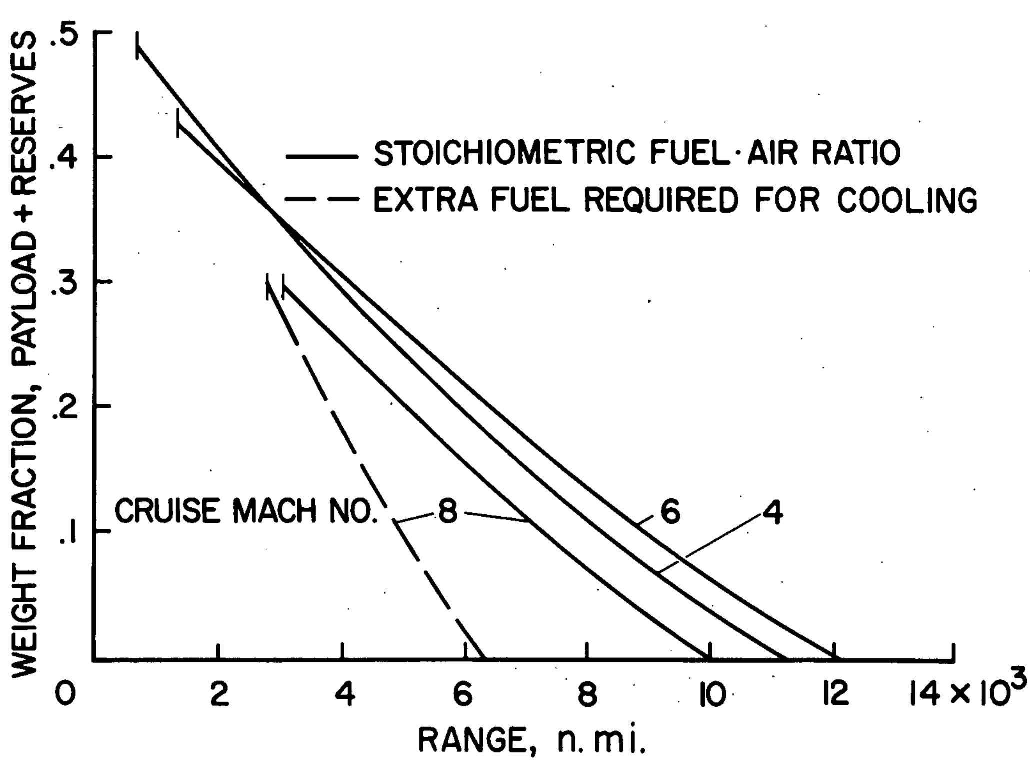

Fig. 15. - Payload-range trade-off.